NASA-CR-203594

/N-89-CR
026196

Cool Stars, Stellar Systems, and the Sun, Eighth Cambridge Workshop
ASP Conference Series, Vol. 64, 1994
Jean-Pierre Caillault (ed.)

CORONAL AND TRANSITION REGION SPECTROSCOPY OF COOL STARS USING EUVE

ALEXANDER BROWN
Joint Institute for Laboratory Astrophysics, University of Colorado & National Institute of Standards and Technology, Boulder, CO 80309-0440 and Center for EUVE Astrophysics, 2150 Kittredge Street, University of California, Berkeley, CA 94720

ABSTRACT The Extreme Ultraviolet Explorer (EUVE) satellite is providing the first opportunity to obtain coronal spectra of a wide range of late-type stars. The spectral resolution and sensitivity of EUVE far exceed the capabilities of previous instruments. Over the 15 month period since launch EUVE has observed 20 cool stars both as calibration targets and GO targets. These spectroscopic data are reviewed and the capabilities of the instrument illustrated. A wide range of coronal conditions are observed including cool ($\sim 10^6$ K) and hot ($\geq 10^7$ K) coronae. Very high coronal densities ($\sim 10^{13}$ cm^{-3}) are observed for Capella, HR1099, and during a large flare on AU Mic. Time-resolved spectroscopy is feasible with EUVE for bright sources and an example (AU Mic) is presented.

INTRODUCTION

EUVE offers the first widely applicable method for obtaining stellar coronal spectra. Coronal spectroscopy allows the physical conditions, such as the distributions of temperature and density, in stellar coronae to be determined. When these physical properties are known, the structure of coronae and the processes leading to their structuring and heating can be investigated.

Prior to EUVE the only coronal spectra obtained in the EUV were EXOSAT Transmission Grating Spectrograph (TGS) spectra of Procyon (α CMi), Capella (α Aur), and σ^2 CrB (Schrijver 1985, Lemen et al. 1989). EUVE provides a factor of 6 improvement in spectral resolution ($R \sim 200$) over the TGS. Instrumental details for the EUVE spectrographs are provided by Welsh et al. (1990), Bowyer and Malina (1991) and Haisch et al. (1994). EUVE observes simultaneously over three spectral ranges: short (SW, 70-190 Å), medium (MW, 140-380 Å), and long (LW, 280-760 Å). The spectral resolution ranges from $\sim$ 0.5 Å in the SW to $\sim$ 1 Å in the MW and $\sim$ 2 Å in the LW. Simultaneous with spectral observations, the Deep Survey (DS) photometric detector also observes the same field through a Lexan filter covering the same spectral region as the SW spectrometer.

Absorption of EUV photons by the interstellar medium is one of the major factors determining the visibility of sources with EUVE. Typically bright coronal

EUVE sources are both intrinsically bright (i.e. large coronal volume emission measure) and nearby (e.g. within 50 pc for RS CVn binaries and within 10 pc for M dwarfs).

EUVE SPECTRAL OBSERVATIONS OF COOL STARS

Early EUVE spectroscopic observations have tended to concentrate on sources known to be relatively bright from the ROSAT WFC and EUVE photometric surveys (Pounds et al. 1993; Malina et al. 1994). Table 1 lists the cool stars that have been observed by EUVE between launch on 1992 June 7 and 1993 October. Clearly there are strong biases in this sample towards active stars such as RS CVn binaries, dMe flares stars, and active dwarfs. However this sample of stars allows many of the most fundamental problems concerning stellar coronae to be investigated. Typical EUVE observations extend over several days with integrated exposures for cool stars of 60-120 ksec. Future observations are likely to be even longer. Such extensive coverage is particularly valuable for studying variable emission due to flares, rotational modulation, and eclipses. In fact many of the cool stars observed so far by EUVE have proved to be variable.

TABLE 1
COOL STARS OBSERVED BY EUVE AS OF OCTOBER 1993

Star	Spectral Type	Date	PI	Coronal T_{high}	Class	Variab-ility ?
AT Mic	M4 Ve	92 07 01	—	7.2	XXIII	Flare
AU Mic	M0 Ve	92 07 14	—	7.2	XXIII	Flares
HR1099	K1 IV + G5 IV	92 10 24	Brown	7.2	XXIII	Yes
Capella	G0 III+ G8 III	92 12 10	Dupree	7.2	XVIII	
Procyon	F5 IV-V	93 01 11	Schmitt	6.3	IX	No
χ^1 Ori	G0 V	93 01 26	Haisch		XVIII	
σ Gem	K1 III +	93 02 06	Schrijver	7.2	XXIII	
31 Com	G0 III	93 02 11	Ayres	7.2	XXIII	
YZ CMi	M4.5 Ve	92 02 25	Bowyer			
AD Leo	M4.5 Ve	93 03 01	Simon	7.2	XXIII	Flare
ξ UMa	G0 Ve + G0 Ve	93 03 28	Schrijver	7.0	XVIII	
ξ Boo	G8 V	93 04 02	Jordan			
Prox Cen	M5 Ve	93 05 21	Bowyer			
α Cen	G2 V + K1 V	93 05 29	Schrijver Mewe			
α Aql	A7 V	93 06 27	Schmitt			
70 Oph	K0 V	93 07 02	Jordan			
UV Cet	M5.5 Ve + M5.5 V	93 08 18	Fossi			
EQ Peg	M4 Ve + M6 Ve	93 08 28	Fossi			
EV Lac	M4.5 Ve	93 09 10	Ambruster	7.2	XXIII	Flare
HR1099	K1 IV + G5 IV	93 09 16	Brown	7.2	XXIII	Flares
II Peg	K2-3 IV-V +	93 10 01	Linsky			

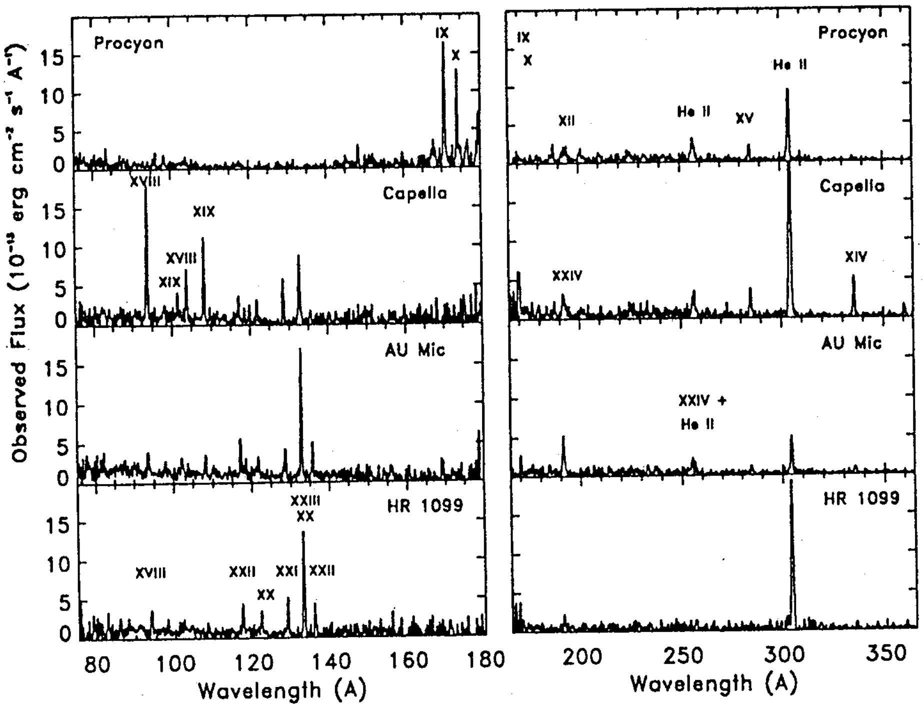

FIGURE I EUVE calibration spectra of Procyon, Capella, AU Mic and HR1099. Prominent Fe lines are indicated by their ionization stage.

TEMPERATURE AND EMISSION MEASURE DISTRIBUTIONS

The first question that EUVE spectra can address is the range of temperature distributions present among stellar coronae. Previously this topic has been studied using Einstein SSS and EXOSAT TGS spectra and X-ray photometry. In Figure I EUVE SW and MW calibration spectra are shown for four cool stars. It is immediately clear that these spectral distributions differ significantly. The F dwarf Procyon shows a much cooler spectrum dominated in the SW region by Fe IX and X emission, formed at 1×10^6 K, and with the hottest line being Fe XV 284 Å formed at 2×10^6 K. The other three stars show much hotter temperatures with Fe XXIV 192.0 Å , formed at 1.6×10^7 K, being detected. However, for Capella Fe XVIII 93.9 Å is the strongest SW line, while for HR1099 and AU Mic the Fe XXIII/Fe XX 132.9 Å blend is stronger. Emission measure analyses show this blend to be dominated by Fe XXIII for these stars. As a means of classifying EUVE spectra in Table 1, we use "T_{high}", the formation temperature of the hottest detected line, and "Class", the ionization state of the strongest Fe line in the SW spectrum.

EUVE spectra of cool stars have sufficient resolution to allow the identification of many individual coronal emission lines. This is illustrated in Fig. II by the detailed SW and MW spectra of HR1099. These spectra are representa-

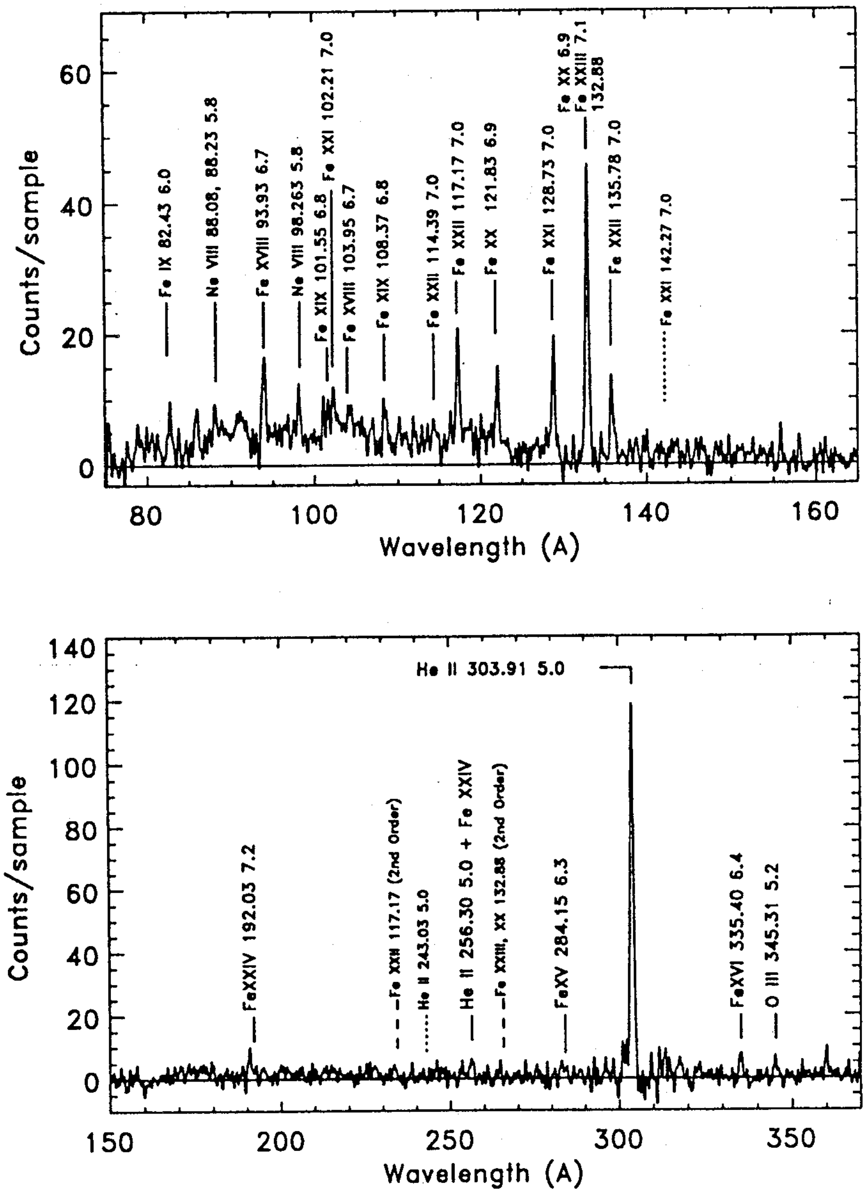

FIGURE II EUVE SW and MW spectra of the RS CVn binary HR1099. Prominent lines are identified by their ionization stage, wavelength, and formation temperature (as a logarithm). Emission from plasma between 10^5 and $10^{7.2}$ K is detected. Note that the only element detected in the corona other than iron is neon. The exposure times were 73 and 75 ksec for the SW and MW detectors respectively. A sample is a 0.067 Å bin. Dotted lines mark the expected positions of undetected lines, while dashed lines mark second order lines.

tive of spectra obtainable for the brightest coronal EUV sources in just under three days of clock time ($\sim$ 75 ksec exposure time). EUVE spectra are heavily oversampled with emission lines spanning roughly 14 pixels in the dispersion direction. Since the EUVE detectors are highly linear photon counting devices, EUVE spectra can be manipulated to significantly enhance the signal-to-noise of the reduced spectra. These HR1099 spectra have been smoothed in the Fourier domain to supress noise on scales of 2 and 3 samples, where a sample is a bin one pixel wide integrated in the cross-dispersion direction. This procedure reduces noise significantly, while retaining essentially the full EUVE resolution.

The observed emission line fluxes can be used to determine the *volume emission measure* (VEM = $\int N_e^2 dV$), which is a parameter that quantifies the amount of emitting plasma present as a function of temperature. The VEM, when evaluated at the peak ionic abundance, is given by

$$VEM = \frac{\Delta N_{el}\, 4\pi d^2 f_{obs}}{\epsilon}$$

where ϵ is the line power output, ΔN_{el} is any elemental abundance difference relative to standard compilations, d is the stellar distance, and f_{obs} is the observed line flux. This calculation can be performed as a function of temperature to derive VEM(T) for each line. EUV line and continuum emissivities have been presented by a number of authors. Compilations which are particularly useful include Mewe et al. (1985,1986), Landini and Monsignori Fossi (1990), Raymond and Smith (1977), and Raymond (1988). However, major uncertainties still exist concerning the ionization balance and atomic data for some relatively important ions, e.g. Fe IX. Emission measure analyses of EUVE spectra tend to proceed in two particular directions; either a statistical fitting of the whole spectrum or detailed analyses of the fluxes of individual emission lines. Both methods have their advantages. The statistical approach is illustrated by Mewe et al. (1994) who analyze EUVE spectra of ξ UMa and σ Gem. In order for this method to be stable the spectra are usually binned to ensure sufficient signal-to-noise. Theoretical emissivity spectra are then compared statistically with the observed spectral distribution and the amount of emitting plasma estimated as a function of temperature. Errors in any individual spectral line are thus minimized and the whole information content of the spectrum is used. Monsignori Fossi and Landini (1993) perform a similar analysis for AU Mic. The alternative approach is to calculate the VEM for individual strong emission lines and determine the general VEM locus that satisfies the behaviour of all the lines analyzed. Dupree et al. (1993) present an example of such an analysis for Capella.

EUVE spectra so far analyzed show lines formed over a wide range of electron temperature. In most cases, e.g. Capella and HR1099, a continuous distribution of emitting plasma appears to be present. In other cases, such as ξ Uma and probably Procyon, a well defined single "coronal temperature" seems to be present. Overall the spectral data emphasises the simplistic approach inherent in 2-temperature X-ray photometric fits and the valuable new information that spectral analyses will provide.

CORONAL ELECTRON DENSITIES

The determination of coronal electron densities is a vital role of EUVE spectra. Modelling of stellar coronae and their relation to other atmospheric regions will be much more constrained if the typical densities are established. Most density sensitive emission lines in the EUV are intrinsically weak and if they can be detected at all the implied densities are likely to be high. The density-sensitive behaviour of lines in the EUVE range are discussed in general by Mewe et al. (1985, Tables VIa,b,c) and by Feldman et al. (1992). In Table 2 a variety of density diagnostics from a range of Fe ions formed at a wide range of temperatures are listed with a suitable reference that will lead to the relevant literature for each ion. Many of these lines would only be visible in high signal-to-noise EUVE spectra and their presence would depend on specific coronal conditions. Nevertheless this list should provide a starting point for those attempting to measure N_e. Much of the previous work on density diagnostics has concentrated on quiescent and flaring solar conditions.

TABLE 2
SOME EUV DENSITY DIAGNOSTICS AND SOURCES

Ion	Wavelength	Log T_e	Density Range	Reference
Fe XII	186 - 196 Å	6.2	9-12	Tayal et al. 1991
Fe XIV	211 - 274 Å	6.2	8-12	Keenan et al. 1991
Fe XV	312 - 327 Å	6.3	8-11	Keenan et al. 1993 Dufton et al. 1990
Fe XXI	91 - 145 Å	7.0	11-15	Mason et al. 1979 M-F & L 1994
Fe XXII	114 - 135 Å	7.0	11-15	Mason and Storey 1980 M-F & L 1994

Electron densities at 10^7 K have been derived for three stars. Dupree et al. (1993) used Fe XXI line ratios to estimate the coronal density of Capella. From the Fe XXI ratios $\lambda142.16/\lambda128.73$ and $\lambda145.65/\lambda128.73$ they derive electron densities of log N_e = 13.2 and 12.8 cm^{-3}. The ratio involving Fe XXI 102.35 Å implies a lower density, but, as Dupree et al. discuss, the measured flux for this line appears to be anomalous. For HR1099 the Fe XXII $\lambda114.4/\lambda117.2$ and Fe XXI $\lambda102.35/\lambda128.73$ ratios both imply densities log $N_e \sim 13$ cm^{-3} (Brown et al. 1994a). The third case where density-sensitive lines are detected is during the July 1992 flare event on AU Mic. The Fe XXII 114.4 Å and Fe XXI 142.2 Å lines are detected in the smaller flare superimposed on the decay of the large flare and again imply densities of order 10^{13} cm^{-3} (Brown et al. 1994b). Densities of this magnitude imply that such emission arises in very compact coronal structures.

TIME-RESOLVED SPECTROSCOPY

For bright variable EUV sources EUVE offers the opportunity to split a spectroscopic dataset into a number of time intervals so that the spectroscopic variability can be investigated. In Fig. III we illustrate this capability with time resolved spectra of AU Mic during both quiescence and the large flare event

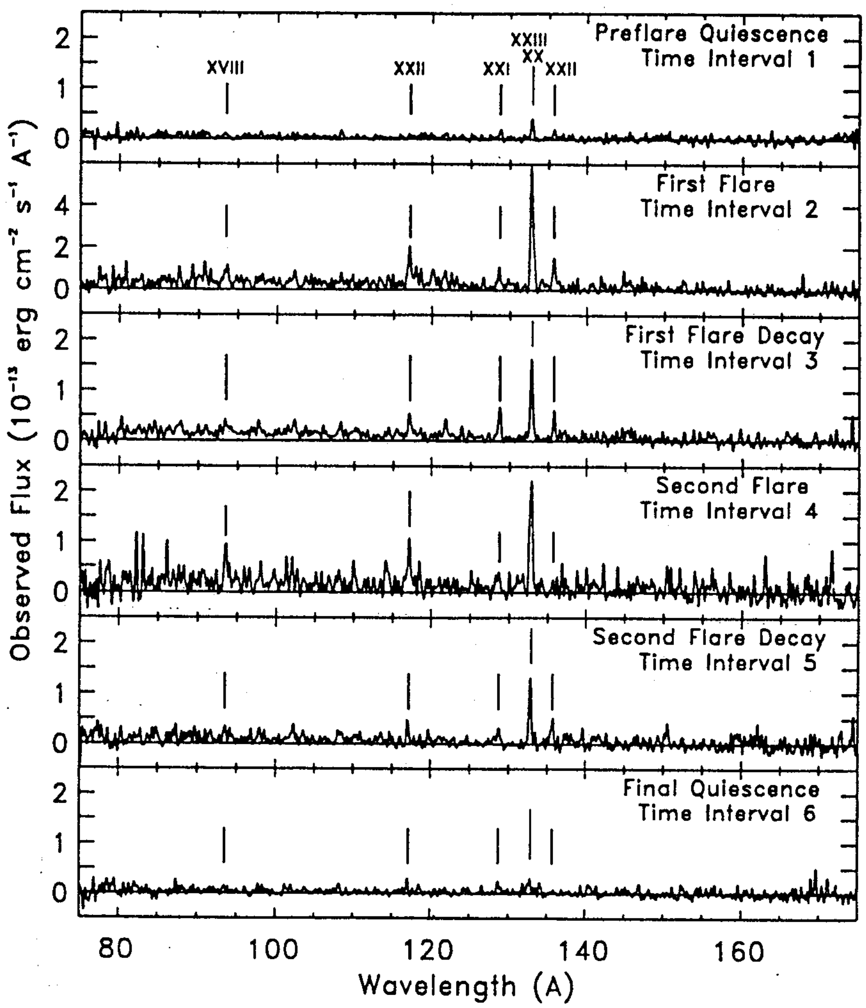

FIGURE III Time-resolved EUVE SW spectra of the flare star AU Mic. The full 85 ksec observation has been divided into six segments based on the morphology of the DS light curve. The initial and final quiescent periods last 26.8 and 11.5 ksec. The two flare intervals are each 3600 seconds long, while the two flare decay intervals last 17.3 and 8.6 ksec.

observed in July 1992. When EUVE data are analyzed in this way the time-dependent spectral behavior becomes readily apparent. For AU Mic the hottest emission lines are found to follow the flare variability closely, while cooler TR lines, such as He II, vary in a much slower manner. However, while some aspects of the variability fit expectations of flare behavior well, other effects, such as the concentration of emission from 10^6 K plasma mostly within the second flare interval, do not. DS photometry of this flare event has been discussed by Cully et al. (1993) and spectral analyses presented by Monsignori Fossi and Landini (1993), Drake et al. (1994), Monsignori Fossi et al. (1994), and Cully et al. (1994). Time-resolved analyses may well be one of the most important contributions that EUVE makes to the understanding of coronal physics.

SUMMARY

- EUVE is providing the first opportunity to study the coronae of cool stars spectroscopically. Because late-type stars represent over half the observable EUV sources, cool star coronal research will be one of the most important astrophysical contributions of EUVE.
- EUVE spectra allow detailed study of coronal temperature distributions. Both continuous and single temperature distributions have been observed.
- Coronal electron densities can be determined from EUVE spectra. In many cases these densities seem to be surprisingly large and indicate that a reevaluation of how stellar coronae are structured may be necessary.
- EUVE spectra allow detailed time-resolved studies of bright variable EUV sources and these studies will provide important constraints of the physical structuring of coronae and flare processes.

ACKNOWLEDGMENTS

I thank the EUVE Science team, particularly Peter Vedder, Jeremy Drake, Bob Patterer, Pat Jelinsky, and John Vallerga, for their cooperation and innumerable insights on EUVE, and the EUVE PIs, Stuart Bowyer and Roger Malina, for allowing me the opportunity to work at CEA. This work was supported by NASA grants NAGW-2904 and NAG5-1792 to the University of Colorado and NASA contract NAS5-30180 to the University of California.

REFERENCES

Bowyer, S. and Malina, R.F. 1991 in *Extreme Ultraviolet Astronomy*, ed R.F. Malina and S. Bowyer (New York: Pergamon), 397.

Brown, A., Linsky, J.L., Vedder, P., Drake, J., and Guinan, E., 1994a, ApJ, to be submitted.

Brown, A., Drake, J., Jelinsky, P., Wu, X., Bowyer, S. and Malina, R., 1994b, ApJ, to be submitted.

Cully, S.L., Siegmund, O.H.W., Vedder, P.W., and Vallerga, J.V., 1993, ApJ, **414**, L49.

Cully, S.L., Siegmund, O.H.W., Fisher, G.H., and Abbott, M., 1994, these proceedings.

Drake J.J., Brown , A., Bowyer, S., Jelinsky, P., Malina, R.F., and Wu, X.Y. 1994, these proceedings

Dufton, P.L., Kingston, A.E., and Widing, K.G., 1990, ApJ, **353**, 323.

Dupree, A.K., Brickhouse, N.S., Doschek, G.A., Green, J.C., and Raymond, J.C., 1993, ApJ, **418**, L41.

Feldman, U., Mandelbaum, P., Seely, J.F., Doschek, G.A., and Gursky, H., 1992 ApJS, **81**, 387.

Haisch, B.M., Bowyer, S., and Malina, R.F., 1994, these proceedings.

Keenan, F.P., Dufton, P.L., Boylan, M.B., Kingston, A.E., and Widing, K.G., 1991, ApJ, **373**, 695.

Keenan, F.P., Dufton, P.L., Conlon, E.S., Foster, V.J., Kingston, A.E., and Widing, K.G., 1993, ApJ, **405**, 798.

Landini, M., and Monsignori Fossi, B.C., 1990, A&AS, **82**, 229.

Lemen, J.R., Mewe, R., Schrijver, C.J., and Fludra, A. 1989, ApJ, **341**, 474.

Malina, R.F., et al. 1994, AJ, in press.

Mason, H.E., Doschek, G.A., Feldman, U., and Bhatia, A.K., 1979, A&A, **73**, 74.

Mason, H.E., and Storey, P.J., 1980, MNRAS, **191**, 631.

Mewe, R., Gronenschild, E.H.B.M., and van den Oord, G.H.J., 1985, A&AS, **62**, 197.

Mewe, R., Lemen, J.R.,and van den Oord, G.H.J., 1986, A&AS, **65**, 511.

Mewe, R., Schrijver, C.J., Kaastra, J.S., Alkemade, F.J.M., and Haisch, B.M. 1994 these proceedings.

Monsignori-Fossi, B.C. and Landini, M. 1993 A&A, **275**, L17.

Monsignori-Fossi, B.C. and Landini, M. 1994 A&A, in press (M-F & L 1994).

Monsignori-Fossi, B.C., Landini, M., Del Zanna, G., and Bowyer, S. 1994, these proceedings.

Pounds, K.A., et al. 1993, MNRAS, **260**, 77.

Raymond, J.C. 1988, in *Hot Thin Plasmas in Astrophysics*, ed. R. Pallavicini (Dordrecht: Kluwer), 3.

Raymond, J.C. and Smith, B.W., 1977, ApJS, **35**, 419.

Schrijver, C.J. 1985, Space Sci. Rev., **40**, 3.

Tayal, S.S., Henry, R.J.W., Keenan, F.P., McCann, S.M. and Widing, K.G., 1991, ApJ, **369**, 567.

Welsh, B., Vallerga, J.V., Jelinsky, P.L., Vedder, P.W., Bowyer, S., and Malina, R.F., 1990, Opt. Eng., **29**, 752.